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Critical Literature Review

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Fiddling While Antarctica Melts? Debates about Antarctica's Role in Sea Level Rise and Implications for Policy Responses

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Abstract: Sea level is rising—but, in spite of attention being drawn to this impact of climate change since the late 1970s, the sheer complexity of attempting to quantify and model potential rises mean that it remains unclear by how much sea levels will rise, at what rate, and where it will impact most. This uncertainty has meant that many policy makers have been unwilling to expend the political capital and resources to take action to counter potentially disastrous –but uncertain –affects. Uncertainty fuels inaction. The role of the Antarctic contribution to sea level rise is critically important because, out of all the contributions to sea-level rise, Antarctic melting has the capacity to greatly affect sea levels. It is already happening in a number of areas, and some models project that melting in Antarctica could accelerate over this century. Should this come to pass, many poorer countries may not have the funds or information to respond in time, as making decisions and finding resources can take decades. To some extent, further research, better data and sharing of knowledge about the contribution of Antarctic melting to sea level rise will help address uncertainties. But policy makers also need to appreciate that, owing to the nature of the system studied and the available sources of data, complete certainty or consensus within the scientific community may not be possible, and hard decisions will need to be made. This review considers the science of and the ongoing debates about Antarctica's contribution to sea-level rise –especially the idea of an acceleration of flow off the glaciers in the Amundsen Sea in the West Antarctic Ice Sheet (WAIS)—and how this information is conveyed to policy makers. It finds that even though much progress has been made by scientists, especially in the past five years, there would be great merit in increasing investments in Antarctic ice sheet research to feed into the next IPCC Assessment Report 6 in five years time. This research should aim to reduce the variance within the scientific community on the issue of WAIS melting, but also help policy makers determine a level of uncertainty at which they would be willing to act, given the risks involved of a possible dynamic response in the WAIS rapidly increasing sea-level rise beyond our capacity to respond. The alternative for the world's scientists, policy makers and planners is neatly encapsulated in one word—Nero.

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Introduction

Sea-level rise is considered to be one of the major consequences of climate change, which, when mixed with other aspects such as more severe storms, will increasingly impact on people's lives, assets and sustaining ecosystems (Brecht et al 2013; Nicholls et al 2011; Oreskes et al 2010; Rahmstorf and Coumou 2011; GRID/UNEP 2009). Understanding the rate, amount and timing of sea-level rise is critically important for scientists and policy makers around the world, both for making decisions about mitigating greenhouse gas emissions, and in adapting to climate change (Karim and Mimura 2008; Malm 2013; Rahmstorf 2012;Vaughan et al 2005). But current estimates of sea-level rise are wide ranging, and scientists disagree over these figures and what contributes to them, especially the potential role of the Antarctic ice sheets which could have larger and more dynamic effects than expected (Ice2Seas 2013; Nicholls and Cazenave 2010; Oreskes et al 2010, Reilly et al 2012).

However, in the world of *realpolitik*, policy makers and communities struggle to handle this uncertainty, preferring definitive advice that will justify potentially costly actions and offer a measure of political protection to decision-making processes (Church et al 2010). On the one hand, further research and efforts to reach consensus amongst the scientific communities will be helpful, while on the other, policy makers need to adopt a more sophisticated appreciation of the scientific process and understanding of statistical advice. Science communicators can help.

Review methodology and approach, sources of evidence and limitations

This paper considers the evidence and debates on Antarctic ice sheet melting, especially the West Antarctic Ice Sheet (WAIS), and efforts to incorporate this factor into sea level models and policy responses to sea level rise. It uses quantitative document analysis to examine journals, reports and books, especially those directed at policy makers. To understand all complexities of the many scientific fields involved (glaciology, meteorology, oceanography, and geodesy) a number of scientific articles are reviewed to compare them with the findings expressed in the science policy documents.

Sea level variability and factors contributing to sea-level rise

Sea level naturally changes but scientists agree that it is currently rising faster than expected. Past sea levels reconstructed from sediment analysis and ice cores have shown that sea level has changed over millennia. However, studies drawing on data from tide gauges have shown that, by the 1800's, the rate of change had dropped to only 0.2mm/year, with sea levels close to today's heights. With advances in satellite altimetry and gravitmetry it is now clear that, due to climate change, this rate has increased again to 1.7mm/year, and since 1993 sea levels have risen by about 3.2mm/year resulting in a global mean sea level rise of 25cm since 1870. (Church et al 2010; Ice2Sea 2013; IPCC AR4 2007; IPCC AR5 2013; SCAR 2009).

Determining the factors that contribute to this sea-level rise is complicated. To date, most sea-level rise has been attributed to melting of mountain glaciers and ice caps, and the thermal expansion of the ocean (IPCC 2013). However, the Intergovernmental Panel on Climate Change (IPCC) 4th Assessment Report (AR4), found that the contribution from Greenland and Antarctica has doubled and has overtaken the role of thermal expansion (IPCC 2007). This process is little understood and affected by many factors including water density (salinity and temperature), movements in the earth's crust, and the shape of the gravitational field (Church et al. 2010). This led the IPCC to state that understanding the contribution of Antarctic ice sheet melting to sea-level rise remains one of the most important outstanding issues that needs to be urgently addressed (Ice2Sea 2013; IPCC 2007; IPCC 2013).

Antarctica's role in influencing sea level – it could be bigger than you think

Antarctica's contribution to sea level is determined by calculating the "mass balance"–the difference between the mass of water entering the continent through increasing snow fall and the mass of water leaving the continent through ice sheet melting, glacial runoff, and evaporation (Wingham et al 2006). But determining this is complex. The data for estimating the mass balance are drawn from a variety of sources from stakes in the ice to satellite altimetry, and changes in gravity to infer mass changes (Steffan et al 2010; Vaughan 2005). Antarctic ice sheet and glacier melt is influenced by breaking up of sea-based ice shelves, ocean temperatures, atmospheric temperatures, the repair of the ozone hole, and the Southern Hemisphere Annular Mode (SAM) which influences the wind (Gille 2002; SCAR 2009; Steig et al 2009; Qui 2012).

Nonetheless, most studies agree that the mass balance of Antarctica is reducing and therefore currently adding to sea-level rise (Shephard and Wingham 2007). Steffen et al (2010) estimated that glaciers and ice caps in Antarctica have had a net loss of mass of 100 Gt/year after 2005 and that this discharges into the ocean through ice streams and outlet glaciers. More recent studies by Little et al (2013) show increasing loss from glaciers and ice sheets across Antarctica. The IPCC concluded that “the average rate of ice loss from the Antarctic ice sheet has likely increased from 30 [–37 to 97] Gt/yr over the period 1992–2001, to 147 [72 to 221] Gt/yr over the period 2002 to 2011.There is very high confidence that these losses are mainly from the northern Antarctic Peninsula and the Amundsen Sea sector of West Antarctica.” (IPCC AR5 2013. P.7)

The West Antarctica Ice Sheet (WAIS) – the one to watch

The potential collapse of the WAIS remains one of the outstanding uncertainties in modelling of Antarctica’s contribution to sea-level rise, and opinion on this continues to evolve. “Collapse” of the WAIS means the loss of the ice sheet due to melting, although it is likely that this would occur as a series of gradual crumbling and melting over a longer time period, rather than the sudden, catastrophic break that the term “collapse” conjures (Vaughan and Spouge 2002). Glaciolost John Mercer first raised this concern in 1968, and whilst further research was conducted in the 1980s, no agreement could be found on whether there was any real threat (Mercer 1978; O’Reilly et al 2012; Vaughan 2008). Others, such as Bentley (1997), argued that collapse of WAIS was very unlikely, and would only result from natural processes, taking centuries. Current thinking is that it remains a possibility, but its likelihood or extent is still uncertain (IPCC 2013).

As such, the potential contribution of the WAIS to sea level rise is a particular focus of current research. (See for example Bamber et al 2009; Ice2Sea 2013; IPCC 2013; Parizek et al 2013; Rignot et al 2011, Rignot et al 2013; SCAR 2009; Shephard and Wingham 2007; Thomas et al 2004; Vaughan and Spouge 2002; Williams et al 2014). This research has found that the WAIS is mostly composed of marine ice (that is, ice that rests on rock that is below sea level), and lies between the Ross and Ronne-Filchner ice shelves (Vaughan and Spouge 2002). It is considered at greater risk of collapse than land ice, because it will be affected both by sea warming and by warming of the atmosphere (Vaughan and Spouge 2002). Should the entire WAIS collapse, it is estimated that global sea level would rise by 5-6 metres. (IPCC 2013).

The main concern of research carried out in the 1970s and 1980s was collapse of the WAIS due to the retreat of the Ross and Ronne-Filchner Ice Shelves .Early assessments were carried out using ice cores taken on the ice shelves close to National Antarctic Bases. (O'Reilly et al 2012). However, new satellite images taken in the late 1990s showed that the glaciers of the Amundsen Sea area were the most dynamic section of the sheet, having the capacity to drain a third of the WAIS, and that, in contrast, the areas bordering the Ross and Ronne-Filchner ice shelves were considered to be quite stable (O'Reilly et al 2012; SCAR 2009; Thomas et al 2004). However, observations of the Amundsen Sea area are difficult because no country claims this region of Antarctica and there are no permanent logistics bases located there. Furthermore, the weather is particular bad, and the region is difficult to reach (O'Reilly et al 2012).

However, more recent studies of these areas using satellite data have showed rapid change in some of the glaciers on this edge of the WAIS. Most seem to be accelerating in their movement, gaining between 2 and 7 times their speed since measurements were first taken. Moreover, the ice in the region is thinning caused by basal melting from warmer seas (Angelis 2003; Rignot et al 2013; Shephard et al 2001). The Pine Island Glacier is now moving at speeds 60% higher than in the 1970s and the Thwaites Glacier shows acceleration and thinning (SCAR 2009; Parizek et al 2013). The current estimated rate of mass loss from these glaciers range from 50 to 137 Gt per year, equivalent to the current rate of mass loss from the entire Greenland ice sheet. These glaciers hold enough ice to raise sea levels by 1.2m-1.5m and it is estimated that they are highly susceptible to climate warming and could make a significant contribution to sea level rise over the 21st century (Parizek et al 2013; Rignot 2011; SCAR 2009; Shephard and Wingham 2008; Steffan et al 2010).

The issues with models – why scientists can't agree

While modelling is at the leading edge of translating science into information for policy, it is far from perfect and leaves many uncertainties. Models on Antarctic ice sheet melting are built around estimates of multiple processes that not very well understood and which reach across scientific disciplines. (O'Reilly et al 2012; Steffan et al 2010).

There are several critical factors that are thought to contribute to the mass balance. These include the basal melting rate (that is, melting of the layer of ice at the bed of Antarctic's glaciers), inter-annual variability, lubrication from melting water, the location of the grounding line (that is, the line that differentiates between ice on sea which doesn't contribute to sea level rise, and ice on land which does), the change in speed of ice streams, ice sheet thinning from underneath, and altitude. However, these dynamic processes are hard to predict and therefore make modelling very difficult (Angelis 2003, Convey et al 2009; O'Reilly et al 2012; Steffan et al 2010; Vaughan and Spouge 2002;). Though understanding has improved due to better in-situ and remote-sensing data, many models do not perform well in replicating past or observed changes and so their ability to project future changes is a challenge. (Cazenave 2008, Nerem et al 2006; Van de Veen 2002).

More analysis in the 2000s brought more data, but also more difficulties for modelling (O'Reilly et al, 2012). Rahmstorf et al (2009) tried to address this by using paleoclimatic data and representing dynamic changes through standard variables. They projected sea-level rise in 2100 to be between 75cm to 190cm metres above the 1990 level (Vermeer and Rahmstorf 2009). The model produced by Rahmstorf has been criticised on statistical grounds and its inability to adequately reproduce observed and modelled sea-level rise (Steffan et al 2010). Bamber et al 2009 undertook a reassessment of the theory and observations of the melting of the WAIS and concluded that previous assessments have *overstated* the WAIS's contribution to sea-level rise. However, other scientists say that these models *underestimate* future contributions to sea level from the Antarctic ice sheets (Steffen et al, 2010). More recent advances have used better equations governing ice flow, used closer grids to obtain higher resolutions, improved data from satellites including the rate of change of the speed of glaciers, and methods to track the change in the grounding line. New methods combining satellite data from different sources has lead to better agreement and certainty of the results (Ice2Sea 2013; Shephard et al 2012).

The debate continues and since the beginning of 2000 at least 29 studies have attempted to estimate the mass balance of the Antarctic ice sheets and their potential contribution to sea-level rise (Kerr 2012). Results continue to range from a mass *loss* of 676 billion tons per year and a huge impact on sea-level rise, through to a mass *gain* of 69 billion tons per year which would reduce the amount of sea-level rise from other sources (Davis et al 2005; Frezzotti and Orombelli 2004; Kerr 2012; Kerr 2012; Shum et al 2008).

Basing policy on uncertain science – the challenge for policy makers

Policy makers need advice on which to devise actions on two fronts—firstly, to develop actions that might avoid a collapse of the WAIS (which requires an understanding of the factors contributing to its melting) and secondly, to develop actions to adapt to sea level rises (which requires an understanding of the rate and degree of sea level rise.) (Oppenheimer and Alley 2004; Oreskes et al 2010).

Given the complicated and multidisciplinary nature of the science involved and the variability of models, many policy makers look to the Intergovernmental Panel on Climate Change (IPCC) to provide some sort of definitive statement on which to base decisions. But even in this forum it has proven difficult to reach an agreement on the amount of sea-level rise. For example, the IPCC Assessment Report 3 (AR3) stated that sea level rises could be up to 82cm by 2100. However, IPCC AR4 attempted to assess where the weight of opinion on sea-level rise lay, and, as a consequence, stated that sea levels would likely rise only 18-59cm by 2100. This opinion was based on models which incorporated thermal expansion, mountain glaciers and slow Antarctic ice sheet response but which left out rapid dynamic processes, such as those potentially affecting the WAIS (IPCC 2007, Oppenheimer et al 2007). This led to some researchers raising concerns about the process by which the

IPCC reached its conclusions in the belief that policy makers needed information on more extreme, worst-case findings and that the IPCC was wrong to exclude these (Oppenheimer et al 2007).

Solomon et al (2008) responded to this criticism by saying that IPCC's *Summary for Policy Makers* clearly said that observations suggested a greater impact from Antarctica ice sheet melting but that research into this issue was still in its infancy. Researchers could not agree on the reasons for melting of the WAIS, nor the speed and extent of the melting. Opinions varied widely with some scientists saying that the WAIS melting was simply a transient phenomenon, others suggesting it was related to long-term climate change, others saying that impacts of the WAIS were not going to happen for a long time, and still others saying that dynamic affects would rapidly and greatly contribute to sea-level rise by 2100 (Reilly et al 2012, Solomon et al 2008).

The overall conclusion was that more research and better understanding was needed (Solomon 2008) and a number of initiatives have since been established to attempt to address the concerns raised about the IPCC AR4 report in 2007 and to present policy makers with better certainty about the amount of sea-level rise – especially the main outstanding uncertainty about the contribution of the WAIS. For example, an initiative from the Scientific Committee on Antarctic Research (SCAR) in 2009 attempted to consolidate scientific opinion and present it in a way that was useful to and understandable by policy makers. Their summary may have, however, *added* to policy makers' confusion, noting that "recent modeling suggests that by 2100 global sea level may rise by up to 1.4m rather than the IPCC's suggested 59 cm" (SCAR 2009, p. xxiii and p. 346). The basis for this revised estimated was that SCAR felt that the models the IPCC considered did not take into account lubrication of the glaciers by melting water under the ice, disintegration of ice selves from melt pools, or melting of ice shelves from underneath.

There have been considerable efforts in various scientific forums to try to reduce variability in models and reach consensus on the impact of Antarctica on sea level change. For example, in 2011, glaciologists from 47 institutions met for the Ice Sheet Mass Balance Intercomparison Exercise (IMBIE). The group concluded that

Antarctic mass balance was definitely contributing to sea level rise, but that available models were insufficient to reach agreement on the nature and degree of the contribution (Kerr 2012). Another initiative, the European Union's *From Ice to High Seas* (2013), tried to address these issues. Researchers used new process-based models that considered updated understandings of glacial processes and regional climate models. Models also included variables such as the length of the summer melt season (which influences the amount of melt water that speeds ice sheet deterioration). They have concluded that ice sheet contribution to sea-level was likely to be less than many other studies and the IPCC AR4 had estimated (3.5 to 36.8cm by the year 2100). (Ice2Sea 2013). Using "expert elicitation" to explore remaining uncertainties, they estimated a "less-than 1-20 risk of ice sheets contributing to global sea-level rise exceeding 84cm by 2100" (Ice2Sea 2013).

Based on these efforts and other research, the IPCC AR5 (2013) says that climate models have improved considerably since their 2007 report and now factor in the potential contribution of the Antarctic ice sheet. In this most recent report, the estimates for sea-level rise have risen again to a likely increase from between 26–98 cm by 2100 (IPCC AR5 2013). However, the report still says they have a low confidence in the projections concerning the impact of the West Antarctic Ice Sheet because data is still insufficient (IPCC 2013).

These initiatives since AR4 in 2007 added knowledge but due to their inconsistent results may have not addressed the levels of uncertainty that policy makers were hoping to have clarified. The challenge for policy makers is to adopt a more sophisticated appreciation of the scientific process and understanding of statistical advice and to find a way to make hard decisions without the scientific consensus they are looking for. Investment in further research before the next Assessment Report 6 will be required.

Directions for future research – investing for the future

There is urgent need for the international community to improve confidence in estimates of the role of Antarctica in sea-level rise, especially the dynamic responses of the WAIS. While much progress has been made since the 1990's and especially over the past five years, the following investments in additional research are suggested:

- Continuation of a program similar to the Ice to High Seas Program (which ends in 2013) that funds and consolidates research on the contribution of ice to sea-level rise. Extension of the model they developed for understanding regional impact beyond Europe would be useful for better decision making across the world (Ice2Sea 2013).
- Specific and multidisciplinary scientific research on the dynamic aspects of the WAIS (especially the glaciers of Amundsen Sea region) is required to build models that incorporate glaciology, meteorology, geodesy and oceanography. (Oppenhiemer 2007).
- Satellite observations alone will not do this and more in-situ investment in Antarctica will be required to overcome the difficulties of research in an area a long way from any logistics base (O'Reilly 2012).
- Lastly, a number of researchers recommend continuing to support space-based observing such as GRACE, JASON, and the Global Climate Observing Systems. There is also a strong argument for more investment and better sharing of data through a larger and more diverse global database on Antarctic ice sheet mass balance and the WAIS (Church et al. 2010; Church et al 2013).

Conclusion

Sea level is rising, currently by 3mm/year, but this rate is expected to accelerate. While many of the reasons for this increase are quantified with reasonable confidence, some potentially major contributors remain uncertain. One of the most important of these is the potential melting and collapse of the West Antarctic Ice Sheet. Though the probability of this occurring is believed to be low, should it happen, the sheet's collapse would contribute 5-6 metres to global mean sea-level rise at a rate of 10's of centimetres per year (SCAR 2009).

With limited resources it would be important to focus on the areas of most vulnerability and these are the glaciers of the Amundsen Sea region. Current research suggests that these glaciers could contribute 1.2-1.5 metres to sea-level rise, and that, with the current accelerations of these glaciers this rise could happen relatively quickly, starting within the 21st century. Monitoring and understanding these glaciers and modelling their de-glaciations in the near future will be important for scientists, policy makers and planners, as policy and investment decisions for climate change mitigation and adaptation need to be made. But there are challenges due to the complexity of the science, and the remoteness of this region. No country claims this sector of Antarctica, so there are no bases there and as a consequence not many people visit to carry out research. Much of the monitoring of this region is done by satellite. This data helps with our understanding of mass balance, but it does not give us all the data required on the dynamic processes of the ice sheet and glaciers.

The IPCC declines to include the most extreme projections of the potential contribution from these glaciers and the WAIS because the science is too uncertain. While this position reflects statistical likelihoods, it means that policy makers are not being advised on the worst-case scenario. Moreover, the variability in models' projections is exploited by climate sceptics and policy makers as reason for doing nothing. This uncertainty feeds into stakeholders' and the public's perception, which in turn further adds to the drain on policy makers' ability to drive action. More certainty is needed, and this requires a greater investment from the international community in Antarctic field research, continuation of the satellite programs, a better sharing of data between countries, and a multidisciplinary approach (Nicholls et al 2011). Policy makers themselves must, however, appreciate that it may not be possible to eliminate uncertainty within a timeframe that still allows for meaningful action and that holding off making hard decisions for this to eventuate may be fiddling while Rome burns—and Antarctica melts.

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